DISPERSION OF CNG FUEL RELEASES IN NATURALLY VENTILATED TUNNELS

Robert Zalosh
James Amy
Craig Hofmeister
Weining Wang

Center for Firesafety Studies
Worcester Polytechnic Institute
Worcester, MA 01609-2280

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ABSTRACT

The hazard of Compressed Natural Gas (CNG) fueled vehicles operating in unventilated tunnels depends on the effective ventilation velocity induced by traffic flow, wind, and/or temperature differences in the tunnel. Large ventilation velocities rapidly dilute the natural gas accidentally released from the CNG fuel system, but when there is no induced velocity a substantial flammable region of natural gas can accumulate under the tunnel roof. In this study, ventilation velocities have been measured during periods of minimal traffic flow in three unventilated Boston tunnels (the Rutherford Avenue tunnel, the Storrow Drive tunnel, and the Hancock passageway in the Prudential tunnel) and in the Lincoln Square underpass in Worcester. Results indicate that the average velocity over the height of these tunnels was in the range 0.74 m/s to 1.39 m/s, with the magnitude depending on the local width of the tunnel cross-section, the ambient wind, and the rate of traffic flow past the measuring location.

Vapor dispersion calculations have been conducted for fuel line rupture incidents involving equivalent CNG and gasoline fueled vans in a prototypical tunnel with a ventilation velocity varying from 0 to 1 m/s. Results indicate that the size of the flammable vapor cloud produced from a CNG fueled van is significantly smaller than that from a gasoline fueled van providing the ventilation velocity is on the order of 0.10 m/s or higher. <u>Since the average velocities in the four tunnels/underpasses are an order-of-magnitude larger than this critical velocity, CNG vehicles should produce a smaller flammable zone than equivalent gasoline fueled vehicles for fuel spill incidents in these tunnels</u>. These results depend on the fuel system configurations as well as the tunnel ventilation, so that additional analyses would be warranted when and if the vehicle fuel systems differ substantially from those assumed for these calculations.

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1. INTRODUCTION

1.1 Previous WPI Study for CNG Fueled Vehicles in Tunnels

In April 1994, Worcester Polytechnic Institute documented (1) the results of a study comparing the hazards of Compressed Natural Gas fueled vehicles and gasoline fueled vehicles operating in tunnels. The basic premise of the study was that the relative hazards would be determined by calculating the size and duration of the flammable clouds formed from a severed fuel line connected to a full tank of fuel. Comparisons were made for equivalent vehicles; i.e. a CNG fueled van compared to the same van fueled with gasoline, and a CNG fueled bus compared to the same bus fueled with gasoline.

Results of the previous study depended on the tunnel ventilation. In transversely ventilated tunnels and in tunnels with significant (1 m/s) longitudinal velocity, the gasoline vapor flammable cloud was significantly larger than the CNG vapor flammable cloud. However, in an unventilated tunnel the reverse was true; i.e. the CNG flammable cloud was larger than the gasoline vapor cloud.

Based on these results and similar results from other studies of CNG fueled vehicles in transversely ventilated tunnels, the Tunnel Safety Study Steering Committee (which represents pertinent Massachusetts state agencies and the Boston Fire Department) has recommended that CNG fueled vehicles be allowed to operate in ventilated tunnels. However the question of unventilated tunnels required the additional study described in this report.

1.2 Purpose and Scope of this Study

The objectives of this study are:

1) to measure the effective natural ventilation velocities in four unventilated tunnels;

and 2) to analyze the implications of those measurements with regard to the dispersion of CNG and gasoline vapor in the hypothesized incidents of the previous study.

The following four Boston tunnels were selected by the Steering Committee for the velocity measurements:

- Storrow Drive Arlington Street Underpass
- Rutherford Avenue Tunnel in Charlestown
- Prudential Tunnel on the Massachusetts Turnpike

and - Dewey Square (South Station) Tunnel on the Central Artery.

The Committee subsequently learned that the Dewey Square Tunnel was equipped with operating fans to provide forced ventilation. Therefore, the Dewey Square Tunnel was removed from the above list of unventilated tunnels needing velocity measurements. WPI decided to conduct measurements in the Lincoln Square Underpass in Worcester in place of the Dewey Square Tunnel.

Since the ventilation velocities are influenced by traffic flow through the tunnel, and since the primary concern is with low velocities, the velocity measurements have been conducted during periods of minimal traffic. Circumstances varied from tunnel to tunnel as described in Section 2.

The incident scenarios and methodology to be used for the dispersion analysis are the same as used in the previous WPI study (1). Specifically, a vehicle fuel line is assumed to be breached such that the fuel tank is emptied into the tunnel. Fuel flow rates and durations have been calculated for the fuel tanks and fuel lines on a prototypical van that is available in both a conventional gasoline version and in a CNG fueled version.

Dispersion calculations have been conducted with the same computational fluid dynamics computer code used in the previous study. The new calculations have been conducted with smaller ventilation velocities in order to determine the minimum velocity for which the gasoline flammable cloud is larger than the CNG flammable cloud. Results are described in Section 3.

2 TUNNEL VELOCITY MEASUREMENTS

2.1 Instrumentation

Thermoanemometer

A TSI Velocicalc model 8355 thermoanemometer was utilized for the tunnel velocity measurements. This instrument is a hot-wire type thermoanemometer for measurement of air velocity and temperature. It is a portable, battery powered instrument with a 37"(94 cm) telescoping measuring probe. The Velocicalc model 8355 has the capability of measuring temperatures over the range 0.0(-17.8 °C) to 200.0 °F(93.3 °C) and air velocities over the range 0.15 to 50.00 m/s. Its accuracy for temperature is ± 0.5 °F, and for velocity is ± 0.01 m/s for velocities from 0.15 to 2.5 m/s.

It has a response time of 200 msec for velocity measurements and 8 sec for temperature measurements. It can store and average up to 255 individual readings each for temperature and velocity. An adjustable time constant from 1 to 20 seconds allows for a moving average of air velocities in fluctuating or turbulent conditions. The Velocicalc was connected to a laptop computer terminal via a RS-232 serial output port and cable. This allowed data transfer and storage, using Windows Terminal communications software to a battery powered Compaq Contura laptop computer.

Instrumentation Set-up

Test sequences were performed at selected locations inside the tunnels based upon tunnel geometry and initial velocity variation measurements. Measurements were also taken immediately outside the upwind tunnel portals. Elevation profile velocity measurements were taken in the center of the closed traffic lane, and cross-width velocity measurements were taken at a 3 ft. (0.9 m). elevation at approximately 3 ft. (0.9 m) intervals across the closed lane. At each test station velocity measurements were generally taken at 3 ft. (0.9 m) elevation points from road surface to 18 ft. (5.5 m)(or tunnel ceiling) using a telescoping pole and mounting brackets. A diagram of the probe and pole assembly is shown in Figure 1.

Each point of reported measurement for vertical and cross-width profiles was an average of ten readings. The instrument time constant for each reading (number of one second interval measurements) varied from one to ten depending on the tunnel.

Preliminary measurements reported below were performed at the Lincoln Underpass in Worcester, M.A. to gain experience in testing sequences and methods.

2.2 Lincoln Square Underpass Data

Description

Lincoln Square Underpass (officially named the Ernest A. Johnson Underpass) is a tunnel-like structure under Lincoln Square in downtown Worcester. The enclosed portion is approximately 250 ft. (76.2 m)long, 30 ft. (9.1 m)wide, and 14 ft. (4.3 m)high. The two lanes of traffic flow are both in the southbound direction exiting onto Main St. A schematic of the tunnel is shown in Figure 2. The measurements were generally taken on a sidewalk along the east wall of the tunnel, with the thermoanemometer situated about 4 ft. (1.2 m)from the wall.

Data

Preliminary tests were conducted at the Lincoln Underpass on September 9, 1994. A full set of tests was not conducted as the information was for procedure and check out purposes only. Furthermore, unlike the Boston tunnels, a lane of traffic was not closed off for these measurements.

The Worcester Municipal Airport reported the ambient temperature to be approximately 74 °F (23 °C)(at 3:00 PM) and the wind speed to be approximately 8 mph (3.6 m/s), measured at a height of 20 ft. (6.1 m), from the east. At the underpass, the air flow was traveling from North to South; i.e. in the direction of the traffic flow through the underpass. Traffic flow was approximately 3 cars per minute, and individual vehicles did not appear to have a substantial effect upon measured average air velocities. The measured temperature inside the underpass showed a 7 °F drop from the temperature measured outside the South Portal.

Upon initial walk through, location 5 (the approximate half length of underpass) indicated the lowest air velocities. Therefore, an elevation profile was taken at this location. Figure 3 shows a velocity profile at location 5 from the road surface to the 13 ft. (4.0 m)elevation. This figure shows the lowest velocities (about 0.4 m/s) occurring at elevations of 3 ft. (0.9 m)and less, and the highest velocities (about 2 m/s) occurring at the middle elevations (about 9 ft. (2.7 m)) of the tunnel.

Average velocities are reported in Section 2.6. Velocities measured at the 3 ft. (0.9 m)elevation at other locations in the tunnel vary from about 0.4 m/s to about 2.6 m/s as indicated in Figure 3.

A cross width profile was taken at location 4 (20 yards from South Portal), at an elevation of approximately 5 ft. (1.5 m), from the east edge of the tunnel to the center (width) of the tunnel. This data shown in Figure 4b indicates velocities varying from 1.1 m/s to 1.7 m/s across the roadway lane.

2.3 Rutherford Avenue Tunnel

2.3.1 Tunnel Description

The Rutherford Avenue Tunnel is located in Charlestown near the Ryan Playground. As shown in Figure 4, the totally enclosed section of the tunnel is approximately 400 ft. (121.9 m)long and 18 ft. (5.5 m) high. An additional 550 ft. (167.6 m) of roadway is covered but open on the sides from a height of 18 ft. (5.5 m) to 30 ft. (9.1 m). The width of the tunnel was four lanes or about 50 ft (15.2 m). The Northbound side of the roadway was closed for repairs, allowing access to both lanes of the road in that direction.

2.3.2 Ambient Conditions

Measurements were taken in the Rutherford Avenue Tunnel on September 12, 1994 between 2:45 PM and 4:00 PM. The ambient conditions at Logan Airport at that time were: temperature 73 °F (22.8 °C), wind 12 knots (6.7 m/s) out of the WNW. Near the tunnel (see Location 1 on Figure 4), the wind varied but was generally out of the North. The temperature was 78 °F (25.5 °C).

2.3.4 Traffic Frequency and Effect on Velocity Measurements

At the time measurements were taken, about 10 cars/minute were passing by in the Southbound direction. The velocity measurements were made in the closed Northbound lanes, in most cases in the lane furthest from the Southbound traffic, and there was no noticeable effect of individual vehicles on these velocity readings. Since the traffic flow and the ambient wind velocity were in the same direction for these measurements, there is no way to distinguish how each influenced the overall air flow in the tunnel. However, the authors impression was that the ambient wind was the major factor in this relatively short length of

enclosed tunnel.

2.3.5 Location of Measurements

Location 1 - About 200 ft. (61.0 m) from the tunnel entrance. This location gave an indication of the ambient conditions.

Location 2 - Just outside the entrance to the tunnel.

Locations 3 and 3A - At the center of the totally enclosed section (200 ft. (61.0 m)from the portal).

Location 4 - About 50 ft. (15.2 m)from the North Portal.

2.3.6 Velocity Elevation Profiles

At Location 3 measurements of air velocity were taken from the ground almost to the ceiling. A repeat set of measurements were taken for confirmation. Figure 5 is a plot of the resulting data points. Most of the data is in the range 1 to 2 m/s. Average velocities are reported in Section 2.6.

2.3.7 Velocity Fluctuations

During the period that measurements were being taken, the air velocity fluctuated significantly with a time scale of 1 to 20 seconds. These fluctuations were due partially to turbulent wind fluctuations and partially to the effect of traffic variations. A method of averaging out the effect of fluctuating air velocities is to average a number of readings at each height. It was decided that at each height, 10 readings would be taken with each reading representing the average velocity over the preceding 10 seconds. Thus each measurement represents an average value over a period of about 100 sec.

2.3.8 Cross-Section Velocities

In addition to taking measurements at various heights, a set of measurements was also taken from the wall of the tunnel to the median strip at a constant height of 3 ft (0.9 m). (see Location 3A on Figure 7). This data, which is plotted in Figure 6, showed that there was no apparent area along the width of the tunnel that differed significantly in its velocity; in other words, there were no "dead spots" where the air was stagnant.

2.3.9 Temperature

Temperature readings were taken at Locations 3 and 4 and found to be 73.0 °F (22.8 °C)and 73.6 °F (23.1 °C), respectively; i.e. about 5°F lower than the ambient temperature at the entrance to the tunnel..

2.4 Storrow Drive Tunnel

2.4.1 Tunnel Description

The Storrow Drive Tunnel is located in Boston on Storrow Drive near the Clarendon Street on-ramp. As shown in Figure 7, the tunnel contains two lanes of Eastbound (or inbound) traffic. The Westbound traffic goes through a brief underpass which is separated from the tunnel. The tunnel is about 1000 ft. (304.8 m)long , 30 ft. (9.1 m)wide and 15 ft. (4.6 m)high. The width of the tunnel increases to about 40 ft. at the Otter Street Incline.

2.4.2 Ambient Conditions

Measurements were taken in the Storrow Drive Tunnel on October 6, 1994 from 1:00 AM through 3:00 AM. The ambient conditions at Logan Airport at that time were: temperature 47 °F (8.3 °C), wind 8 knots (3.6 m/s) out of the WNW. Near the tunnel (see Location 1 on Figure 7 for Storrow Drive Tunnel), the wind varied but was generally out of the West at a velocity of 0.25 m/s at the 5 ft (15 m) elevation. The temperature was 49 °F (9.4 °C). At the tunnel west portal (Location 2 in Figure 7) the wind velocity was about 2.3 m/s directed in toward the tunnel.

2.4.3 Traffic Frequency and Effect on Data

At 1:00 A.M. when the measurements began, about 6 cars/minute were passing through the tunnel. By 3:00 AM the flow had dropped to 3 cars/minute,. The individual vehicles, which were typically travelling at 30-40 miles per hour (13-18 m/s), had a transient effect on the Velocicalc readings with the wake induced by each vehicle being of approximately 10 to 15 seconds duration. Since each velocity data point was an average over about 100 seconds (i.e. the average of 10 readings, each with a time constant of 10 sec), no single vehicle significantly influenced any of the recorded velocity data. However, the cumulative effect of

the aggregate traffic probably did influence the data because of the long enclosed length of this tunnel.

2.4.4 Location of Measurements

Location 1 - About 200 ft. (61.0 m)outside the West portal, at the top of the entrance ramp. This location gave an indication of the ambient conditions.

Location 2 - Just inside the West portal.

Location 3 - Inside the tunnel about 200 ft. (61.0 m)from the West portal.

Location 4 - Inside the tunnel about 400 ft. (121.9 m)from the West Portal.

Location 5 - Inside the tunnel about 600 ft. (182.9 m)from the West Portal and where the Otter Street Incline branches off from the tunnel.

2.4.5 Velocity Elevation Profiles

At Location 3 measurements of air velocity were taken from the ground almost to the ceiling. At Locations 4 and 5, similar measurements were taken. Figure 8 is a plot of the resulting data points. The velocities are in the range 0.20 to 2.50 m/s, with the lowest velocities at locations 4 and 5 and at the highest elevations. Locations 4 and 5 have lower velocities than locations 2 and 3 because the tunnel cross-section is wider at locations 2 and 3 and because some of the airflow entering the west portal flows out of the tunnel through the Otter Street exit ramp. The velocities were lowest at the highest elevations because these elevations were situated between beams that obstructed the longitudinal flow through the tunnel. Average velocities over the tunnel height are reported in Section 2.6.

2.4.6 Velocity Fluctuations

Root-mean-square (rms) velocity fluctuations were calculated from the data at each location. These rms fluctuations are the standard deviations of 10 readings, with each reading of 10 seconds duration. The rms fluctuations varied from about 0.06 m/s to about 0.27 m/s, representing from 8% to 21% of the average velocities measured at each location. Thus, the turbulent velocity fluctuations were in the range 8 to 21% of the values shown in the figures.

2.4.7 Cross-Section Velocities

In addition to taking measurements at various heights, a set of measurements was also taken from the wall of the tunnel to a distance of 8 ft. (2.4 m)from the wall at a constant height of 5 ft. (1.5 m)(see Location 4A in Figure 6). This showed that there was no apparent "dead spots" where the air was stagnant.

2.4.9 Temperature

A temperature reading was taken at Location 5 and found to be 56.2 °F (13.4 °C), i.e. about 7 °F warmer than the temperature outside the tunnel.

2.5 Prudential Tunnel

2.5.1 Tunnel Description

The Prudential Tunnel is located in Boston on the Massachusetts Turnpike and runs under the Prudential Center. The tunnel is broken into three sections: the Hancock Passageway (735 ft. (224.0 m) long, Eastern portion of tunnel), the Copley Passageway (550 ft. (167.6 m) long, middle portion of tunnel) and the Prudential Passageway (1950 ft. (594.4 m) long, Western portion of tunnel). All of the sections have mechanical ventilation but the ventilation in the Hancock Passageway is not normally turned on. As such, measurements were taken only in the Hancock Passageway since the air velocity was in question there.

As shown in Figure 9, the Hancock Passageway contains three lanes of Eastbound (or inbound) traffic and three lanes of Westbound traffic. The passageway also contains the Back Bay Station of the commuter rail. The passageway is about 735 ft. (224.0 m)long, 60 ft. (18.3 m)wide (not including the added width of the Back Bay Station) and its height varies from 15 ft. (4.6 m)to 23 ft. 4 in (7.1 m). The separation between the two directions of traffic consists of columns spaced about 20 ft. (6.1 m)apart for the first 500 ft. (152.4 m)of the tunnel and a solid wall thereafter.

2.5.2 Ambient Conditions

Measurements were taken in the Prudential Tunnel on October 27, 1994 from 12:00 AM

through 2:30 AM. The ambient conditions at Logan Airport at that time were: temperature 51 °F (16.7 °C), wind 9 knots (4.07 m/s) out of the WNW.

2.5.3 Traffic Frequency

At the time measurements began, about 8 cars/minute were traveling through the two open westbound lanes of the tunnel. By 2:00 AM the flow had dropped to less than 3 cars/minute. The effect of tractor trailers and other large vehicles (which are too high to enter the Storrow Drive tunnel) was felt to be significant for an individual 10-sec velocity measurement but much less significant when averaged over the entire 80-100 sec duration of the 10 measurements which were averaged at each location. The aggregate traffic flow probably did have a significant effect on the overall air flow, but there was no way to separate this effect from the effect of the mechanical ventilation in the adjacent Copley Passageway and Prudential Passageway sections of the tunnel.

2.5.4 Location of Measurements

Location 1 - Just inside East portal.

Location 2 - Parallel to the top of the first on-ramp or inside the tunnel about 200 ft. (61.0 m)from the East portal.

Location 3 - Parallel with the bottom of the on-ramp or inside the tunnel about 400 ft. (121.9 m)from the East portal.

Location 4 - About 100 ft. (30.5 m)past the start of the solid wall median or inside the tunnel about 600 ft. (182.9 m)from the East Portal.

Location 5 - Just before the start of the Copley on-ramp or inside the tunnel about 700 ft. (213.4 m)from the East Portal.

2.5.5 Velocity Elevation Profiles

At Locations 2, 3, 4, and 5 measurements of air velocity were taken from the ground almost to the ceiling. Figure 10 is a plot of the resulting data points. The lowest velocities were measured at the highest locations, which were situated in the quiescent space between beams. Below the bottom of the beams the velocities were in the range 0.50 m/s to 2.2 m/s with average velocities reported in Section 2.6.

2.5.6 Cross-Section Velocities

In addition to taking measurements at various heights, a set of measurements was also taken from the wall of the tunnel to a distance of 9 ft. from the wall at a constant height of 3 ft (0.9 m) (see Location 5A on Figure 9). Air velocity picked up noticeably during this set of measurements as shown by the difference between the 3 ft. (0.9 m)and 6 ft. (1.8 m)measurements. A second measurement at the wall was taken to confirm that the velocity had increased there as well. By taking this increase into account, it appeared that there were no apparent "dead spots" where the air was stagnant.

2.5.7 Temperature

Temperature readings were taken at Locations 1 and 5 and found to be 54.2 °F (12.3 °C)and 61.0 °F (16.1 °C), respectively. These temperatures are 3 °F and 10 °F higher, respectively, than the ambient temperature at the time of the measurements.

2.6 Average Velocities in Each Tunnel

Average velocities for each elevation profile were computed from the equation:

$$\bar{v} = (1/H_{tun})\int_0^{H_{tun}} v\,dz$$

where H_{tun} is the tunnel height.

Results are listed in Table 1. The lowest average velocity is 0.74 m/s at Location 4 in the Storrow Drive Tunnel. The largest average velocity is 1.39 m/s at Location 2 of the Prudential Tunnel. The variation from location to location within one tunnel seemed to be greater than the variations from tunnel to tunnel. In both the Storrow Drive and Prudential tunnels, the smallest vertically-averaged velocity occurred at the location in which the tunnel width was largest because of an entrance or exit ramp. Thus the location of the minimum velocity is consistent with expectations based on mass conservation for steady flow through the tunnel.

The largest vertically-averaged velocity in both the Storrow Drive and Prudential tunnels

occurred at the tunnel entrances. This may be due in part because of the influence of ambient winds at the tunnel entrances and/or in part because those measurements were made when the traffic frequencies were greatest.

The average air velocity for all the measurement locations in the four tunnels is 1.11 m/s.

Table 1 also shows the ratio of the velocity at the road surface (about 1 cm above the surface) to the average velocity above the surface at each measurement location. This ratio varied substantially from location to location. The average ratio for all the measurement locations was 0.80.

Table 1

Vertically-Averaged Velocities

Tunnel	Location	Average Velocity (m/s)	Ground Vel/Avg*
Lincoln Underpass	5	1.19	38%
Rutherford Avenue	3	1.11	73%
	3 -repeat	1.36	76%
Storrow Drive	3	1.34	68%
	4	0.74	105%
	5	0.91	49%
Prudential Tunnel	2	1.39	98%
	3	0.84	111%
	4	1.14	99%
	5	1.04	84%
Average		1.11	80%

* Average here is without ground velocity and without the measurements taken at Storrow Drive and Prudential that were above the beams.

3. VAPOR DISPERSION CALCULATIONS

3.1 Release Scenarios and Calculation Methodology

Fuel flow rates from ruptured fuel lines under the van were calculated as described in Reference 1. In the case of the CNG fueled van, a 1/4-inch (0.635 cm) diameter fuel line was assumed to be breached at the connection to a 1270 scf (24 kg) capacity cylinder charged to 3000 psig (20.7 MPa). CNG choked isentropic flow for this configuration produces an initial flow rate of 0.79 kg/s and an average flow rate of 0.35 kg/s over the 68 sec blowdown.

In the case of the gasoline fueled van, a 1/2-inch (1.27 cm) diameter breached fuel fill line was assumed to occur at the bottom of a filled 35 gallon (159 liter) capacity gasoline tank. The gasoline is assumed to spill onto the road surface and the resultant gasoline pool simultaneously spreads and evaporates. The mathematical model used to simulate the spill, spreading, and vaporization of the gasoline was described in Reference 1. The particular version of the model used for the new calculations was a three component representation of gasoline as 53%-pentane, 22%-hexane, and 25%-benzene, such that its Reid vapor pressure would be about 9 psia (465 mm Hg) and its vapor pressure at 20 °C is 272 mm Hg (5.3 psia). The viscosity of gasoline was taken as 5.0×10^{-7} kg/m-s which is substantially lower than the value used in the previous calculations.

The calculated CNG release rates and gasoline vaporization rates were used as input to the vapor dispersion calculations performed with the computational fluid dynamics (CFD) code FLUENT Version 3. FLUENT solves the governing partial differential equations for conservation of mass, momentum, energy, and chemical species. The computational domain is discretized and the finite difference form of the equations is solved for velocity, temperature, pressure, and species concentration, in each computational cell. In this application, the computational domain was a 100 ft (30.5 m) long section of a 27 ft (8.25m) wide by 14 ft (4.27 m) high tunnel. The tunnel was divided up into a 30x20x20 computational grid.

In most cases, steady-state FLUENT dispersion simulations were conducted based on the

average CNG release rates and the average gasoline vaporization rates. Each of these simulations typically consumed several days of computer time on a multi-user DECstation 5000/260 at WPI.

The primary results examined for each simulation were the size and shape of the flammable cloud as delineated by the lower flammable limit concentration contour. The lower flammable limit for CNG (methane) is 5.0 vol%, while the lower flammable limit for gasoline vapor was taken as 1.6 vol % (which according to Reference 2 is midway between the lower limits for pentane and butane). Thus the gasoline cloud requires much more air dilution than the methane cloud to reach concentrations at and below the flammable limit.

3.2 Comparison of Gasoline and CNG Flammable Clouds

Both the gasoline and the CNG dispersion simulations were conducted for several different longitudinal velocities within the range 0 to 1 m/s. Results are shown in Figures 11 through 16. Note that the vertical scale in these figures is stretched relative to the horizontal scale.

Figures 11a and 11b show the calculated flammable vapor regions for a tunnel ventilation velocity of 0.65 m/s. The flammable region resulting from the gasoline spill (Figure 11a) is much larger than corresponding flammable region from the CNG release (Figure 11b). The upper edge of the gasoline vapor flammable cloud extends from the van to the downstream end of the tunnel, a distance of about 50 m. The height of the cloud above the road surface is roughly equal to the van height (2.0 m) at the van and decreases to about 1 m at the downstream end of the tunnel. There is a sizeable region under the gasoline van in which gasoline vapor concentrations exceed the upper flammable limit (8.3 v%). In the case of the CNG release, the flammable region is limited to the immediate vicinity of the van.

Calculated results at a velocity of 0.30 m/s are shown in Figures 12a and 12b for gasoline and CNG, respectively. shows the gasoline vapor flammable cloud at a tunnel ventilation velocity of 0.30 m/s. Results are similar to those at 0.65 m/s but the gasoline flammable vapor region is even larger at 0.30 m/s. Near the downstream end of the tunnel, the gasoline flammable region extends from the road surface to the full height of the tunnel.

Figures 13a and 13b show the flammable clouds at a longitudinal ventilation velocity of 0.20 m/s. The gasoline vapor flammable region is still substantially larger than the CNG (methane) flammable region at 0.20 m/s, but now the methane flammable region extends to the roof of the tunnel because buoyancy velocities are now larger than longitudinal velocities in the wake of the van.

Figure 14 shows the CNG (methane) flammable region reaching the downstream end of the tunnel at a ventilation velocity of 0.13 m/s. The depth of the methane flammable cloud varies from about 4 m at the van to 1.4 m at the downstream end of the tunnel. Thus the size of the CNG (methane) flammable cloud is substantially larger at 0.13 m/s than it is at velocities of 0.20 m/s and higher.

Figures 15a and 15b show the flammable clouds when the ventilation velocity is reduced to 0.10 m/s. Now both the methane and gasoline vapor flammable cloud occupy the entire downstream half of the tunnel and even extend upstream of the van. The gasoline vapor flammable cloud is now only marginally larger than the methane flammable cloud.

Figures 16a and 16b show the gasoline vapor and methane flammable clouds in an unventilated tunnel with zero longitudinal velocity. In this extreme case, the gasoline flammable cloud is confined to a thin (about 0.69 m deep) cloud above the road surface, while the methane flammable cloud is confined to a somewhat deeper (1.2 m deep at the van) cloud under the roof. In this case there is symmetry on both sides of the van, so the clouds extend at least 100 m (the length of the calculation zone) in both directions from the van.

3.3 Discussion of Results

In the naturally ventilated tunnels of concern in this report, the size of the flammable cloud depends on the vapor release rate, the lower flammable limit concentration, and the positive or negative buoyancy of the vapor. Since the lower limit concentration for gasoline vapor (1.6 vol%) is considerably lower than that of methane (5.0 vol%), if the other two factors (vapor release rate and buoyancy) are equivalent, we should expect a larger gasoline vapor flammable cloud than a methane flammable cloud. Furthermore, pentane is more negatively buoyant (vapor specific gravity of 72/29 = 2.5) than methane is positively buoyant (vapor

specific gravity of 16/29 = 1/1.8), so buoyancy also renders the gasoline cloud somewhat larger.

Figure 17 is a graph of the calculated gasoline spill vaporization rate (averaged over time) as a function of the tunnel ventilation velocity. The vaporization rate increases from about 0.10 kg/s at zero ventilation velocity to about 1.1 kg/s at a ventilation velocity of 1 m/s. The time-averaged CNG release rate of 0.35 kg/s is independent of ventilation velocity as shown in Figure 17. The gasoline vaporization rate exceeds the CNG release rate at ventilation velocities higher than about 0.10 m/s. Using the reasoning in the preceding paragraph, we should expect the gasoline flammable cloud to be larger than the CNG cloud for ventilation velocities higher than some value which is in the range 0 to 0.10 m/s.

The volumes of the CNG and gasoline vapor flammable clouds are plotted as a function of ventilation velocity in Figure 18. The data are only estimated volumes based on approx-imating the lower flammable limit contours by simple geometric shapes and ignoring the variation across the tunnel width. Furthermore, the volumes only extend to the end of the computation zone which is 50 m downstream from the van for nonzero ventilation velocities.

The estimated cloud volumes plotted in Figure 18 illustrate the benefits of higher ventilation velocities in reducing the size of the flammable cloud as long as the velocity is at least 0.10 m/s. When the ventilation velocity is less than 0.10 m/s, the gasoline cloud becomes smaller, while the CNG cloud becomes still larger. The steepest reduction in CNG flammable cloud volume seems to occur for velocities in the range 0 to 0.20 m/s.

It is clear from Figure 18 that the gasoline vapor flammable cloud is larger than the CNG flammable cloud for velocities of about 0.03 m/s and higher. However, the results shown in Figures 17 and 18 are approximate in that they were obtained with theoretical models which don't account for complications such as multiple vehicles, a sloped road surface, and drainage grills. Furthermore, the gasoline vaporization and dispersion calculations employed the same velocity whereas the data in Table 1 indicate that the road surface velocities (needed for the vaporization calculations) are lower than the vertically average velocities (used for the vapor dispersion calculations). The net effect of these complications would probably alter the results

slightly by rendering the gasoline vapor cloud somewhat smaller than shown in these figures. However, the crossover velocity above which the gasoline flammable cloud is larger than the CNG flammable cloud would still probably be on the order of 0.10 m/s.

As a final comment, the reader is reminded that these results are based on the hypothesized fuel system incidents. In particular, the size of the CNG flammable cloud is based on the size of the broken fuel line and the capacity of the CNG cylinder. These are the sizes currently used in a typical CNG van. If the fuel line were significantly larger, or if the CNG cylinder itself was breached, the CNG flammable cloud would indeed be much larger. Therefore, it would be prudent to monitor the evolving status of CNG fuel system design and CNG vehicle operating experience to determine the continued applicability and reality of the hypothesized incident scenarios.

4. CONCLUSIONS

1. Air velocities have been measured in four unventilated tunnels and overpasses in Boston and Worcester during periods of minimal traffic flow. The velocities averaged over the tunnel height were in the range 0.74 m/s to 1.39 m/s in these tunnels. The average velocity for all the measurements was 1.11 m/s.

2. CNG dispersion calculations have been conducted for a hypothesized incident involving the rupture of a 1/4-inch fuel line from a van in a 14 ft high longitudinally ventilated tunnel with ventilation velocities in the range 0 to 1 m/s. Results indicate that the flammable region is limited to the immediate vicinity of the van when the ventilation velocity is at least 0.20 m/s. When the effective ventilation velocity is less than about 0.20 m/s, the vapor accumulates under the tunnel ceiling and the flammable region occupies a significantly large area of the tunnel.

3. Gasoline spill, vaporization, and dispersal calculations have also been conducted for a conventional fueled van in tunnels with longitudinal ventilation velocities of 0 to 1 m/s. Results indicate that the flammable cloud occupies a substantial portion of the tunnel downstream of the van when the ventilation velocity is about 0.10 m/s or higher. When the tunnel ventilation velocity is zero, the flammable cloud is confined to a shallow layer above the road surface.

4. The comparison of the gasoline and CNG dispersion calculations demonstrates that the size of the flammable region from an incident involving a CNG fueled van is significantly smaller than the flammable region from a comparable incident involving a gasoline fueled van as long as the effective ventilation velocity is at on the order of 0.10 m/s or higher. Since the average ventilation velocities in the four tunnels are an order-of-magnitude larger than this, CNG fueled vans can be expected to produce smaller flammable regions than gasoline fueled vans given a fuel line rupture incident in these tunnels.

5. REFERENCES

1. Zalosh, R., Pilette, Y., Wang, W., "Hazard Analysis of Alternative Fueled Vehicles in CA/T Tunnels, Part 1: CNG Fueled Vehicles" WPI Report for Bechtel/Parsons Brinckerhoff and Massachusetts Highway Department, April 1994.

2. Zabetakis, M.G., "Flammability Characteristics of Combustible Gases and Vapors," Bureau of Mines Bulletin 627, 1965.

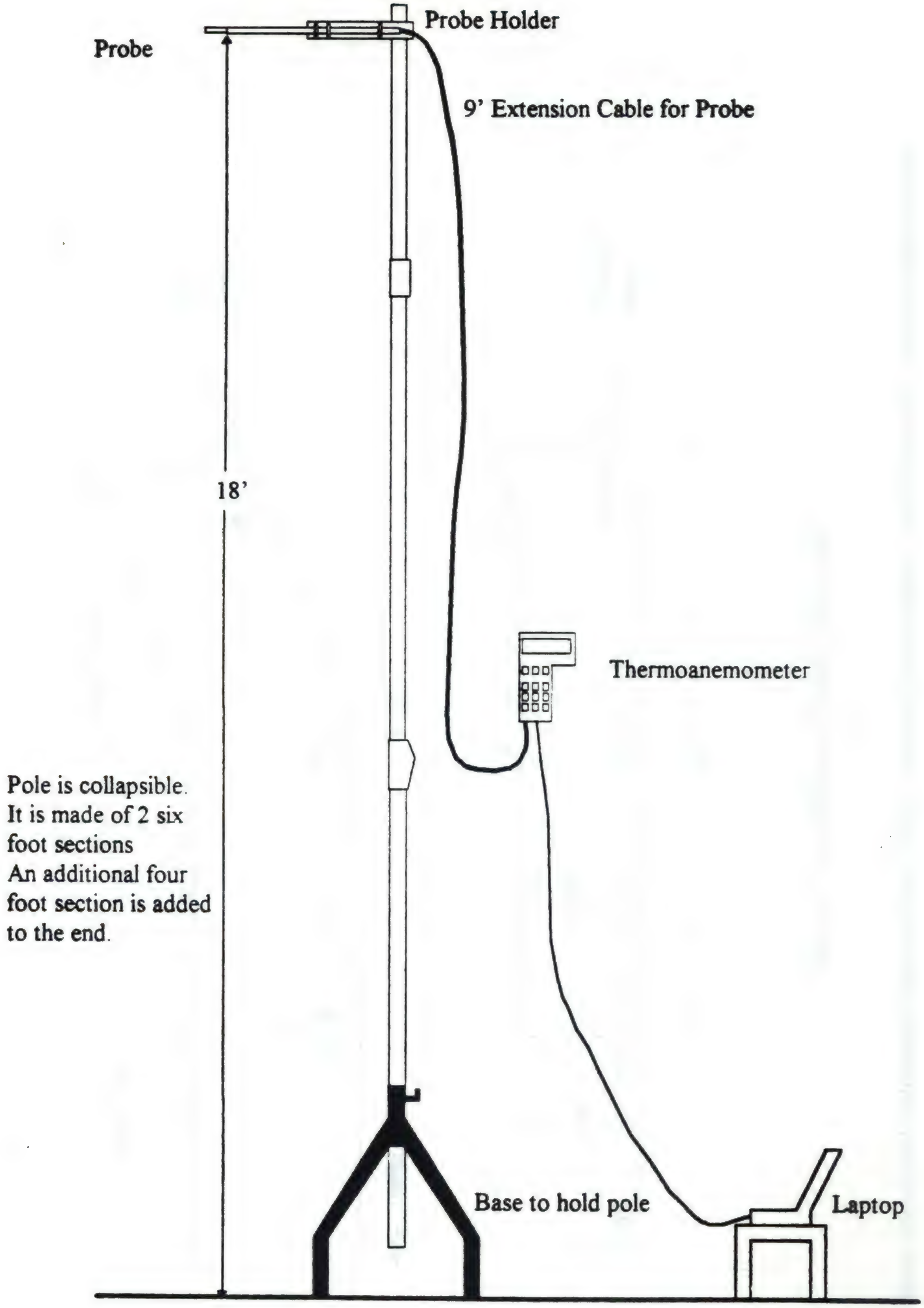

Figure 1 - Setup for Measurements Using Thermoanemometer

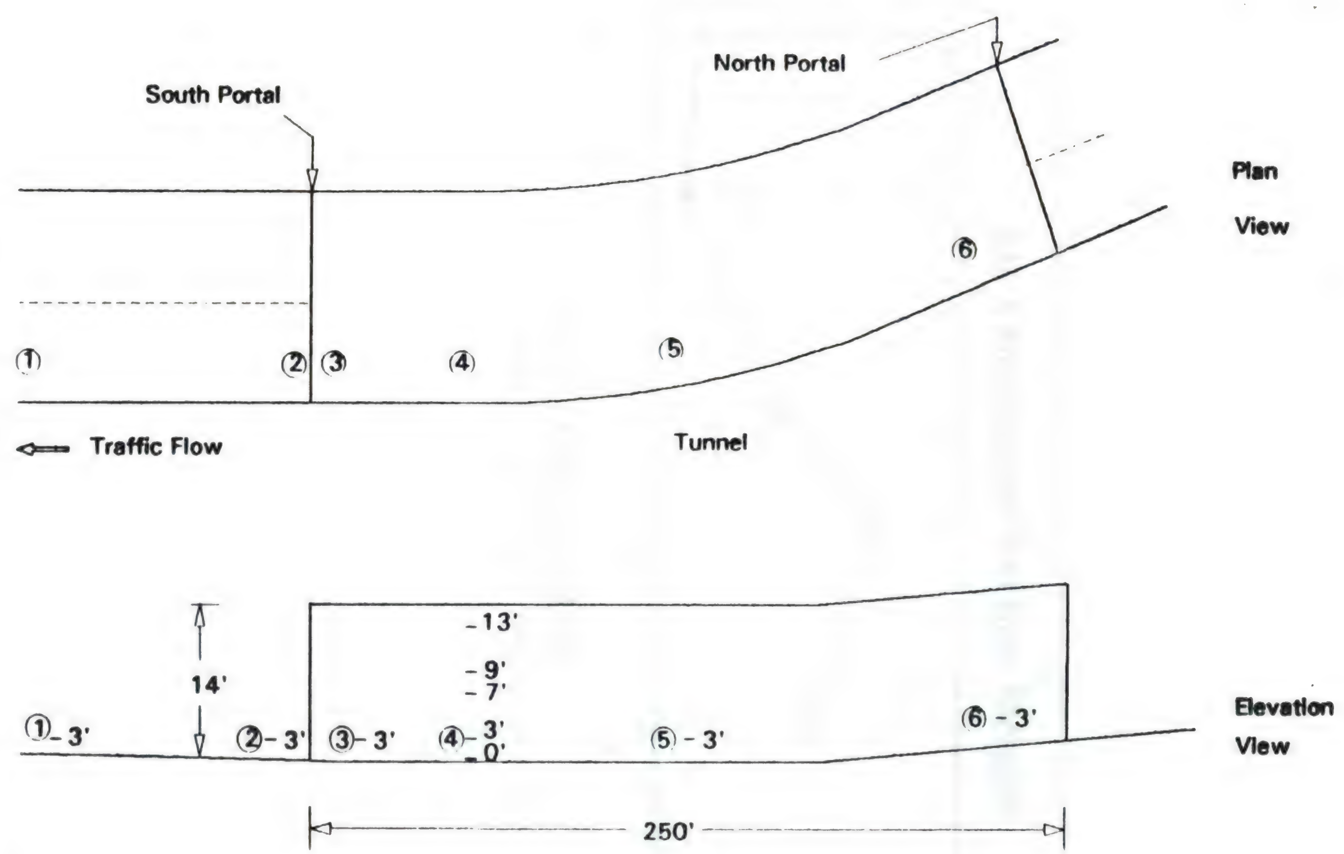

Figure 2 - Lincoln Square Tunnel (not to scale)

This figure shows the locations and elevations at which air velocity measurements were taken with the thermoanemometer.

1 foot = 0.3048 meters

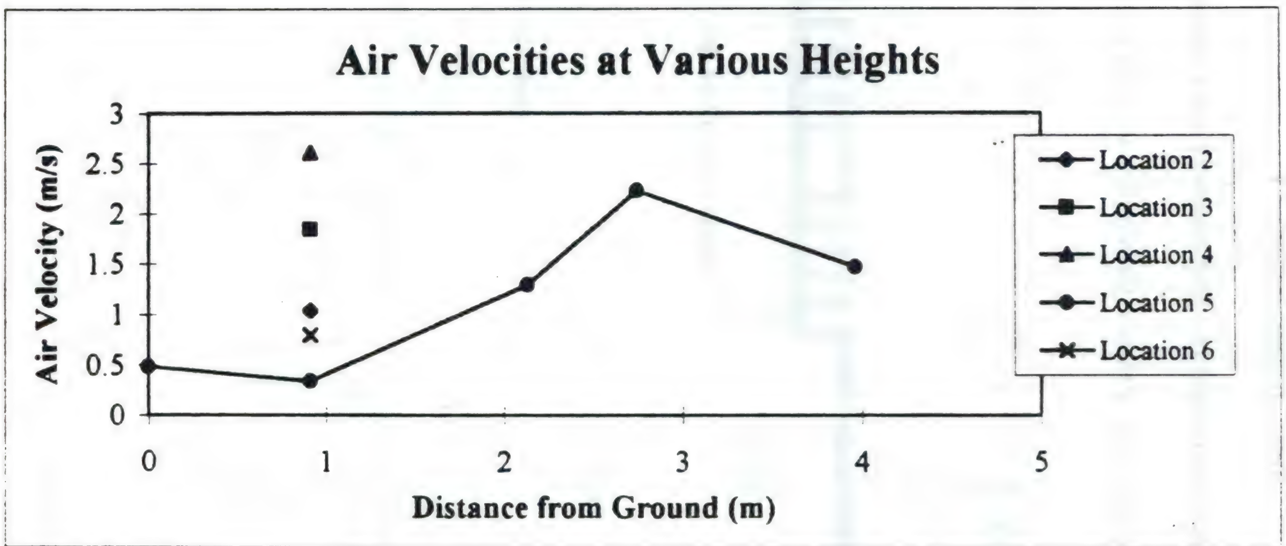

Figure 3 - Graph of Lincoln Underpass Air Velocity Data

This graph contains the air velocity data measured at the locations and elevations shown in Figure 2.

Note: Heights in Figure 2 have been converted to SI units for this graph.

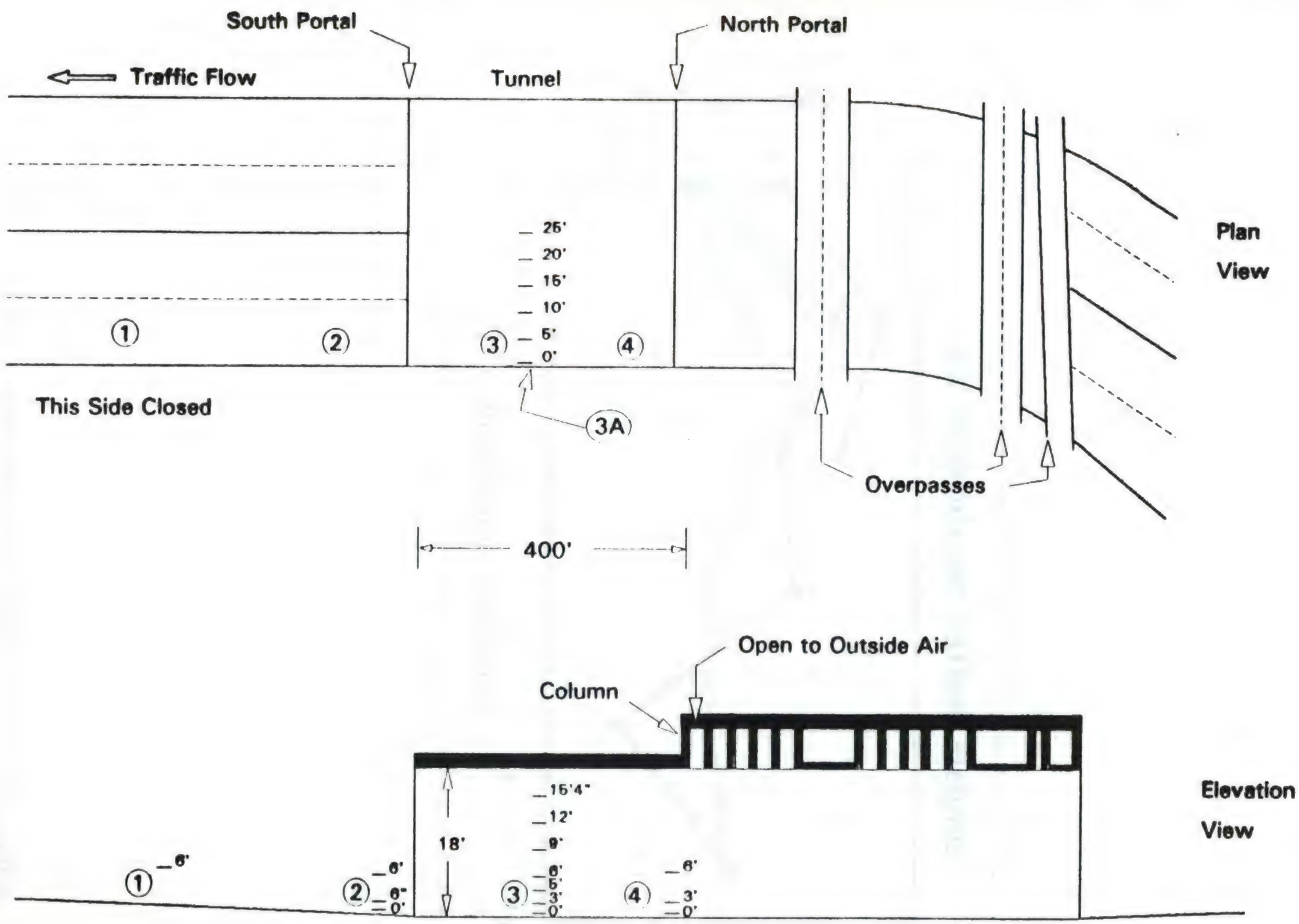

Figure 4 - Rutherford Avenue Tunnel (not to scale)

This figure shows the locations and elevations at which air velocity measurements were taken with the thermoanemometer.

1 foot = 0.3048 meters

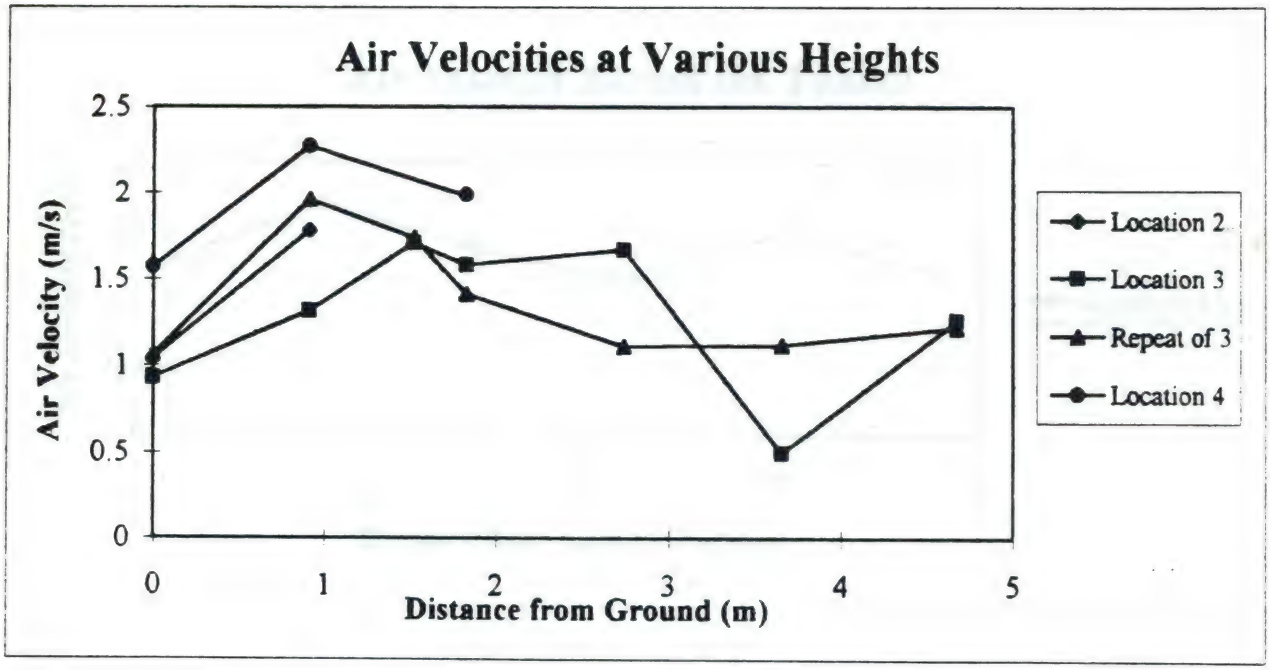

Figure 5 - Graph of Rutherford Avenue Tunnel Air Velocity Data

This graph contains the air velocity data measured at the locations and elevations shown in Figure 4.

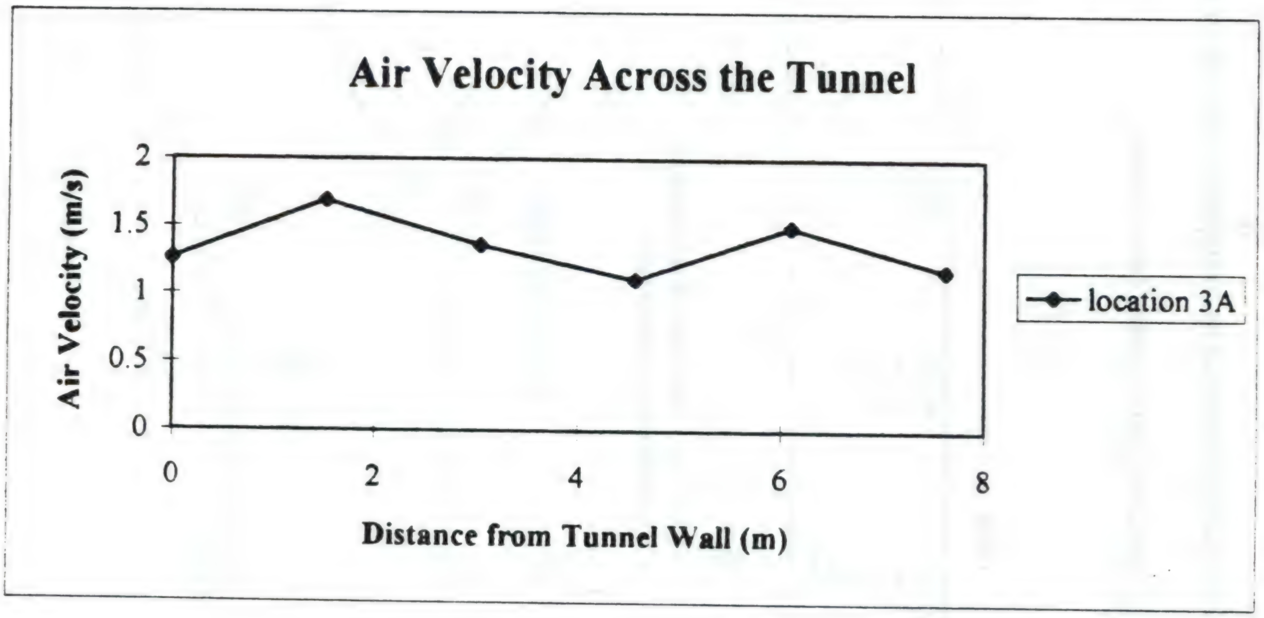

Figure 6 - Graph of Air Velocity Across Rutherford Avenue Tunnel

This graph contains the air velocity data measured at Location 3A as shown in Figure 4.

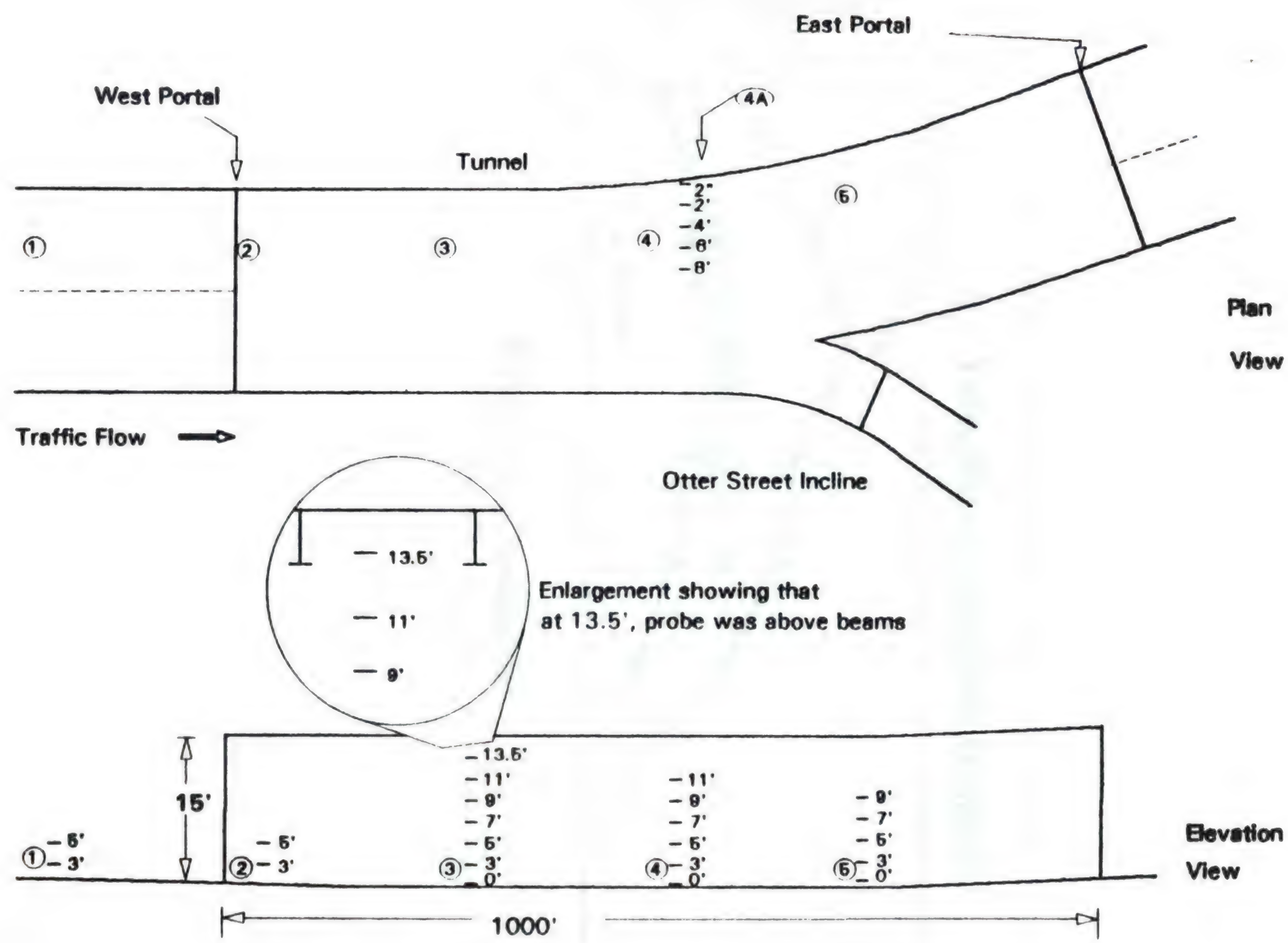

Figure 7 - Storrow Drive Tunnel (not to scale)

This figure shows the locations and elevations at which air velocity measurements were taken with the thermoanemometer.

1 foot = 0.3048 meters

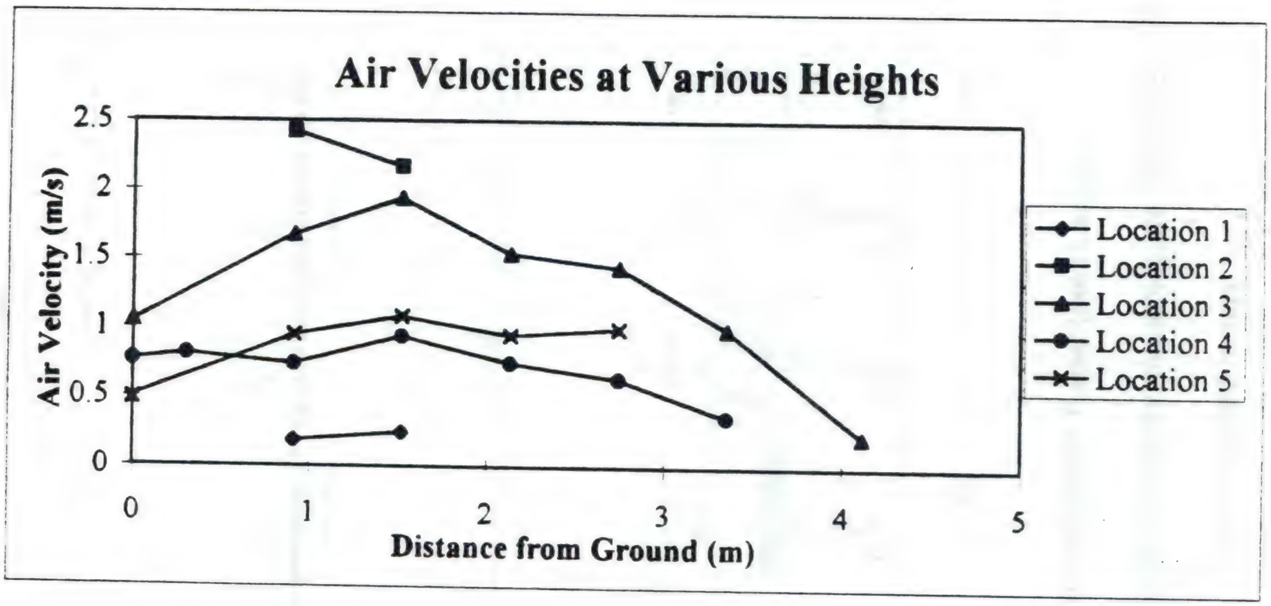

Figure 8 - Storrow Drive Tunnel Air Velocity Data

This graph contains the air velocity data measured at the locations and elevations shown in Figure 7.

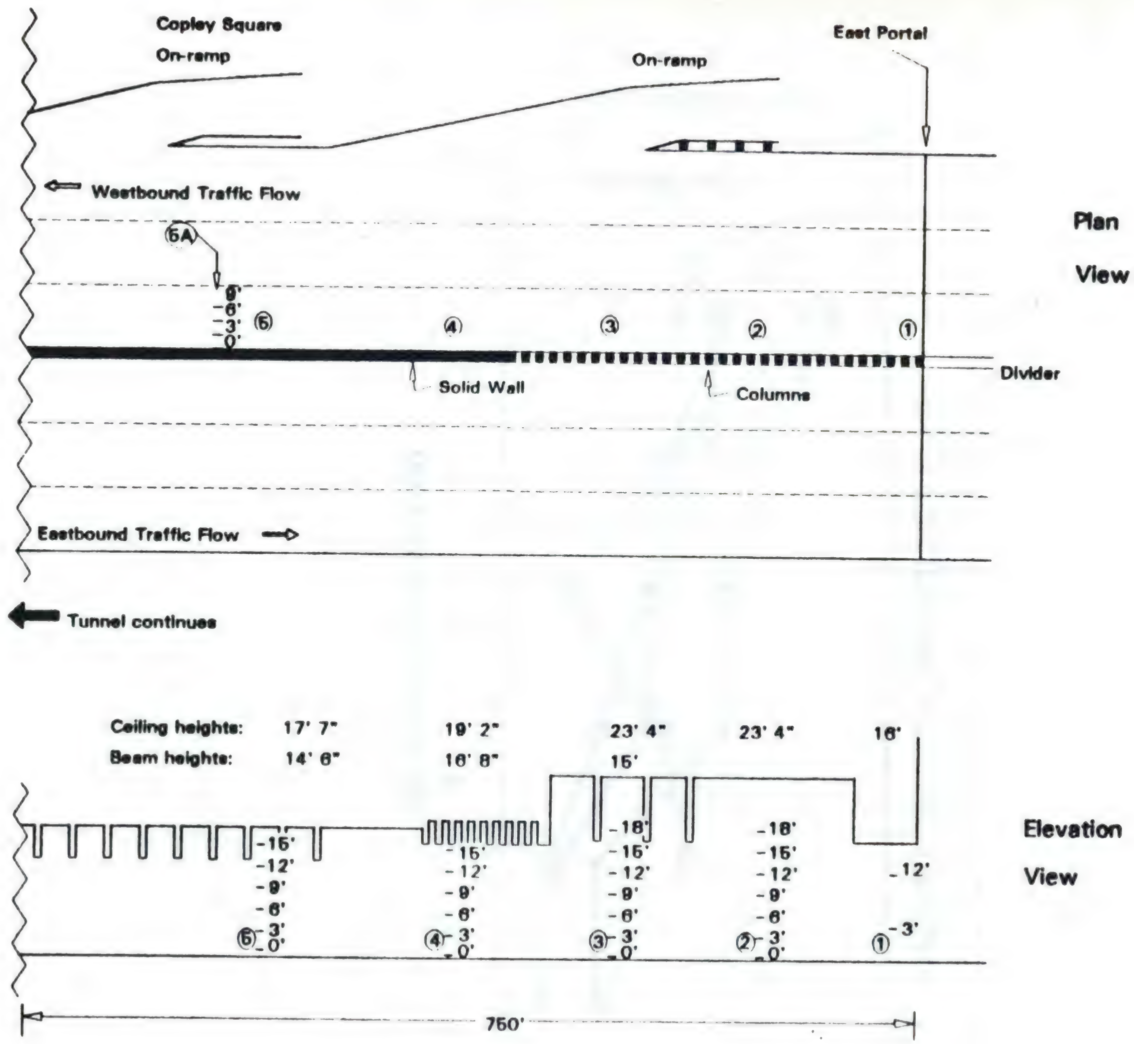

Figure 9 - Prudential Tunnel (not to scale)

This figure shows the locations and elevations at which air velocity measurements were taken with the thermoanemometer.

1 foot = 0.3048 meters

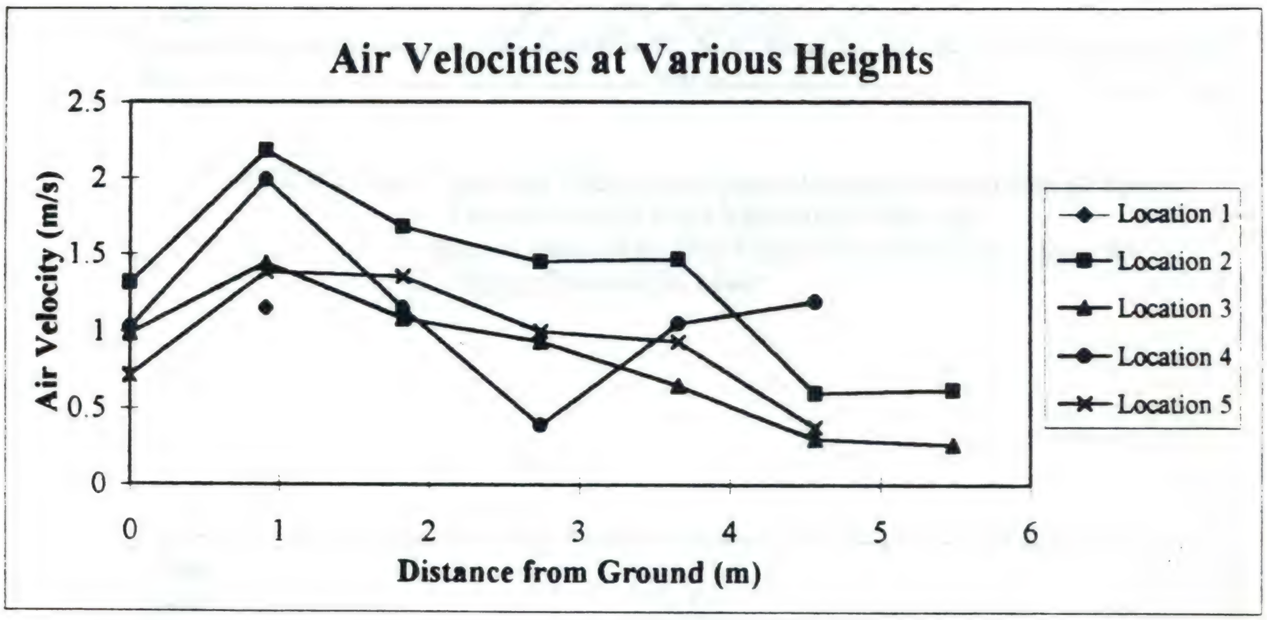

Figure 10 - Graph of Prudential Tunnel Air Velocity Data

This graph contains the air velocity data measured at the locations and elevations shown in Figure 9.

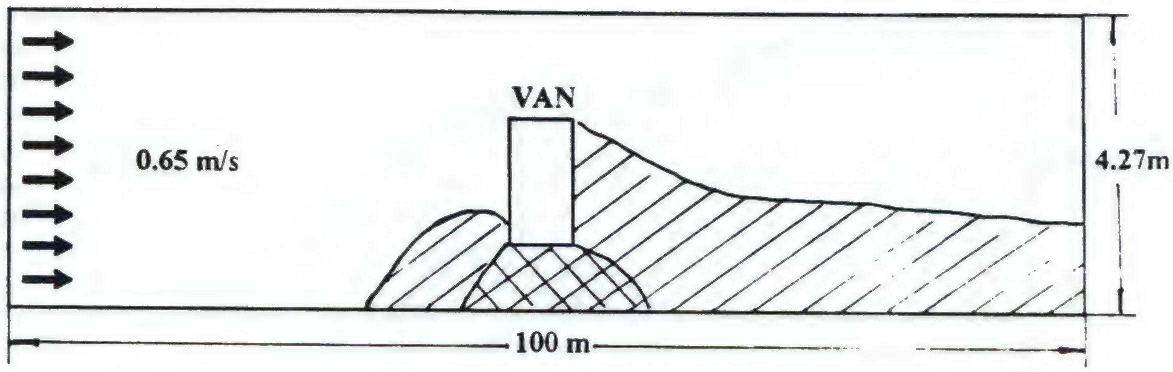

FIGURE 11(a). Gasoline Flammable Vapor Region Downstream of Van in Tunnel with 0.65 m/s Ventilation Velocity
Region under Van Has Vapor Concentrations above the Upper Flammable Limit.

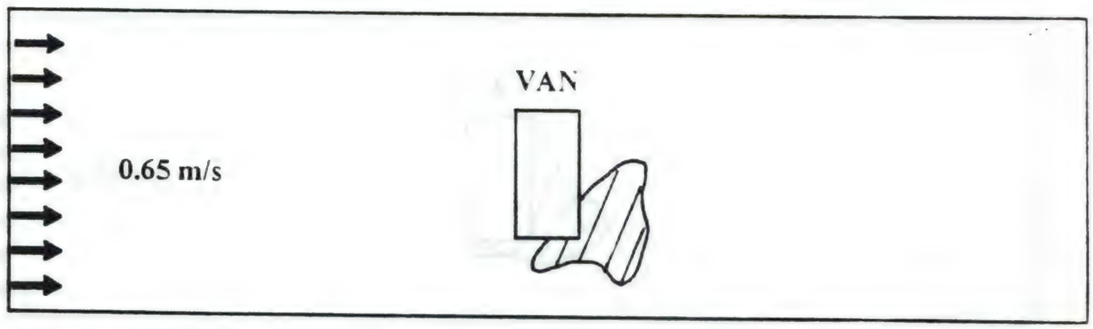

FIGURE 11(b). CNG Flammable Region Downstream of Van at a Ventilation Velocity of 0.65 m/s

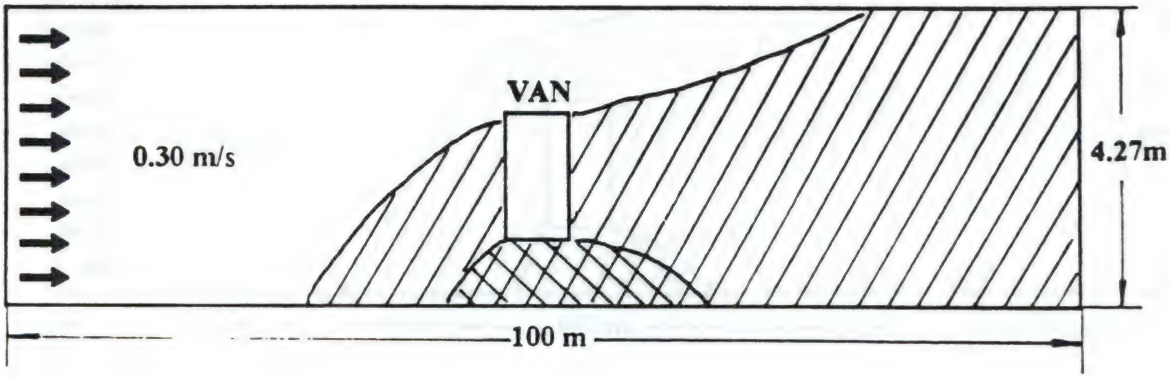

FIGURE 12(a). Gasoline Flammable Vapor Region Downstream of Van in Tunnel with 0.30 m/s Ventilation Velocity
Region under Van Has Vapor Concentrations above the Upper Flammable Limit.

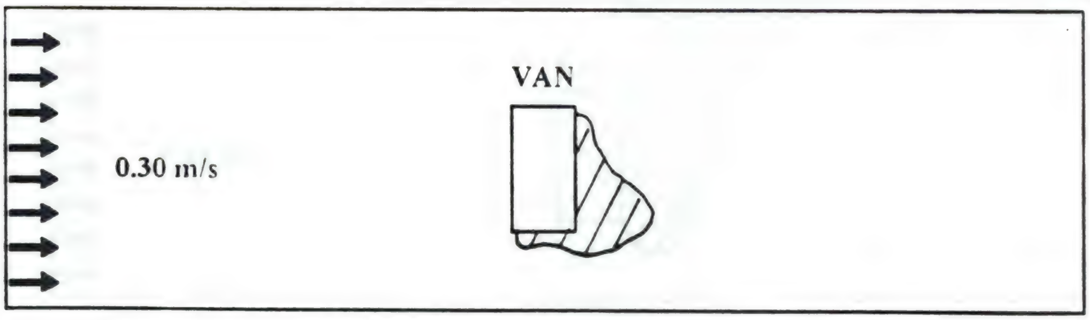

FIGURE 12(b). CNG Flammable Region Downstream of Van at a Ventilation Velocity of 0.30 m/s

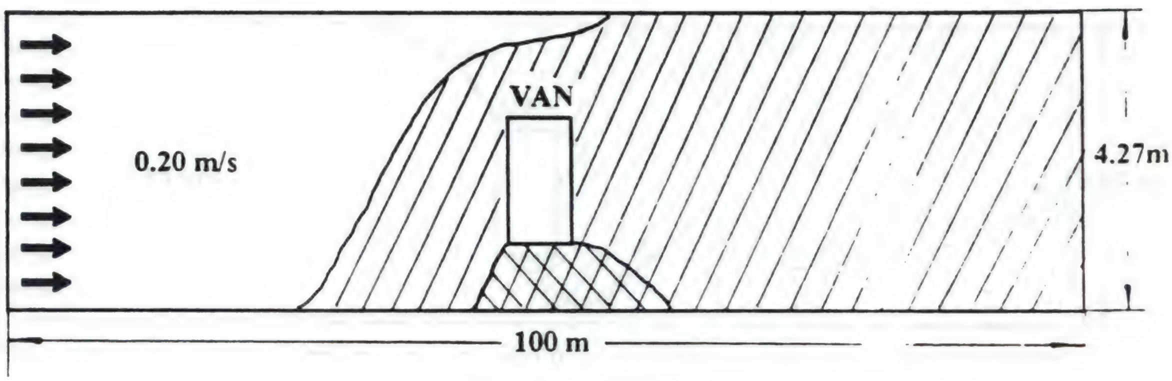

FIGURE 13(a). Gasoline Flammable Vapor Region Downstream of Van in Tunnel with 0.20 m/s Ventilation Velocity Region under Van Has Vapor Concentrations above the Upper Flammable Limit.

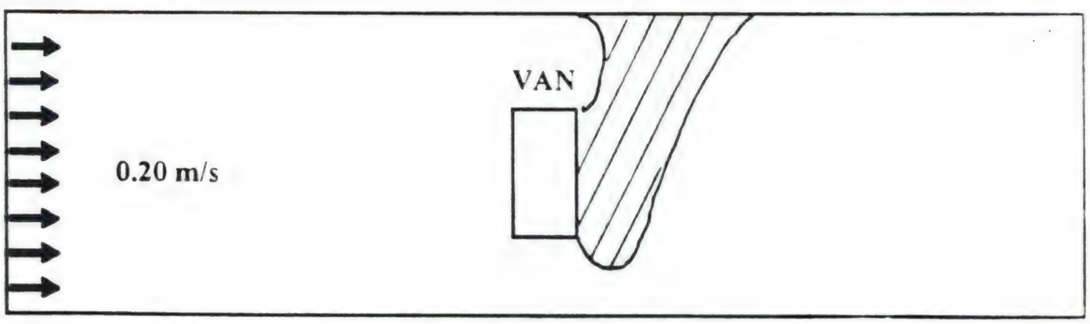

FIGURE 13(b). CNG Flammable Region Downstream of Van at a Ventilation Velocity of 0.20 m/s

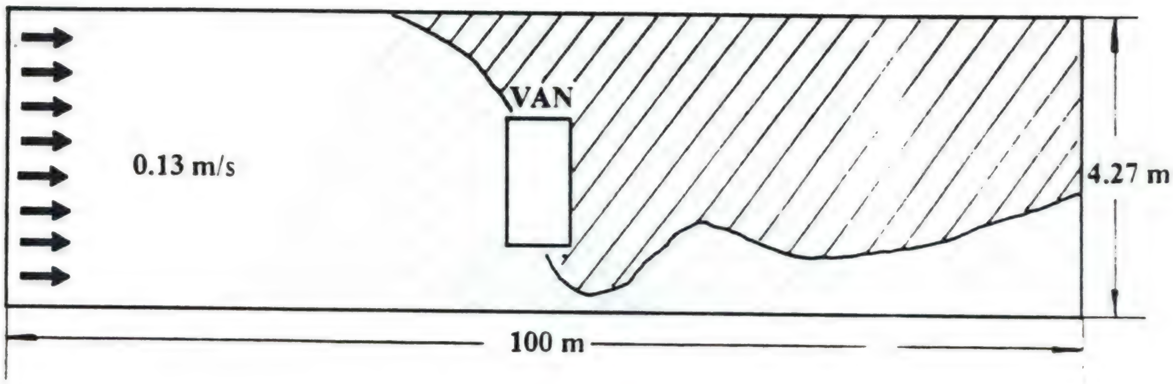

FIGURE 14. CNG Flammable Vapor Region Downstream of Van at a Ventilation Velocity of 0.13 m/s

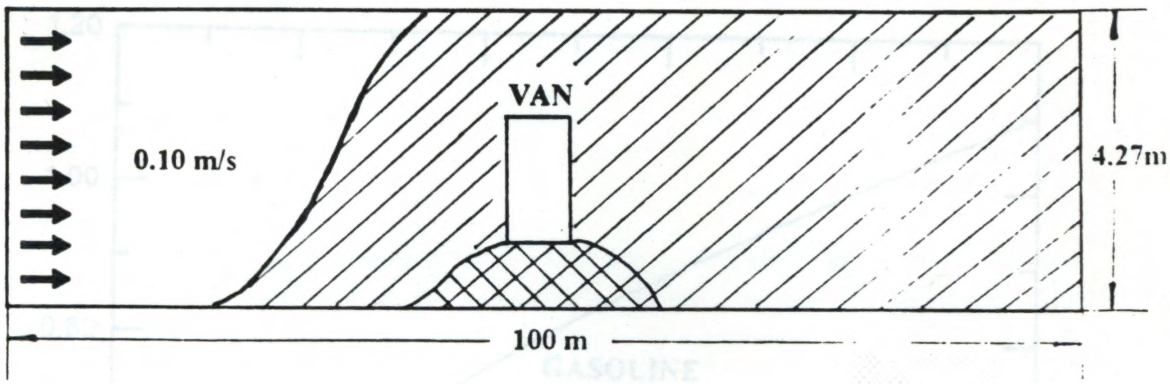

FIGURE 15(a). Gasoline Flammable Vapor Region Downstream of Van in Tunnel with 0.10 m/s Ventilation Velocity
Region under Van Has Vapor Concentrations above the Upper Flammable Limit.

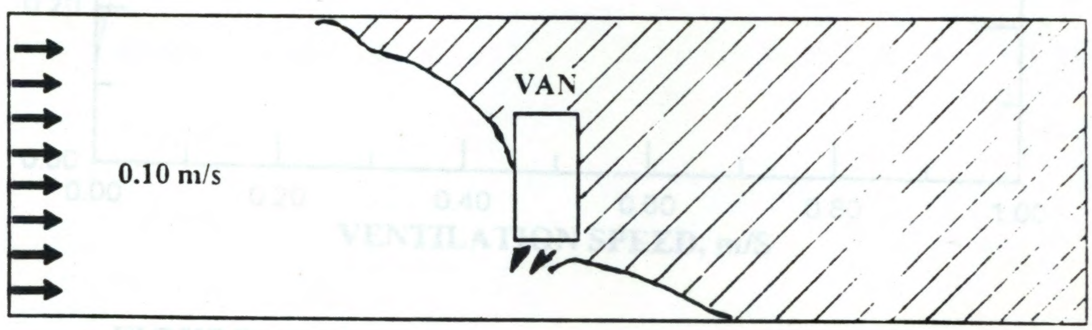

FIGURE 15(b). CNG Flammable Region Downstream of Van at a Ventilation Velocity of 0.10 m/s

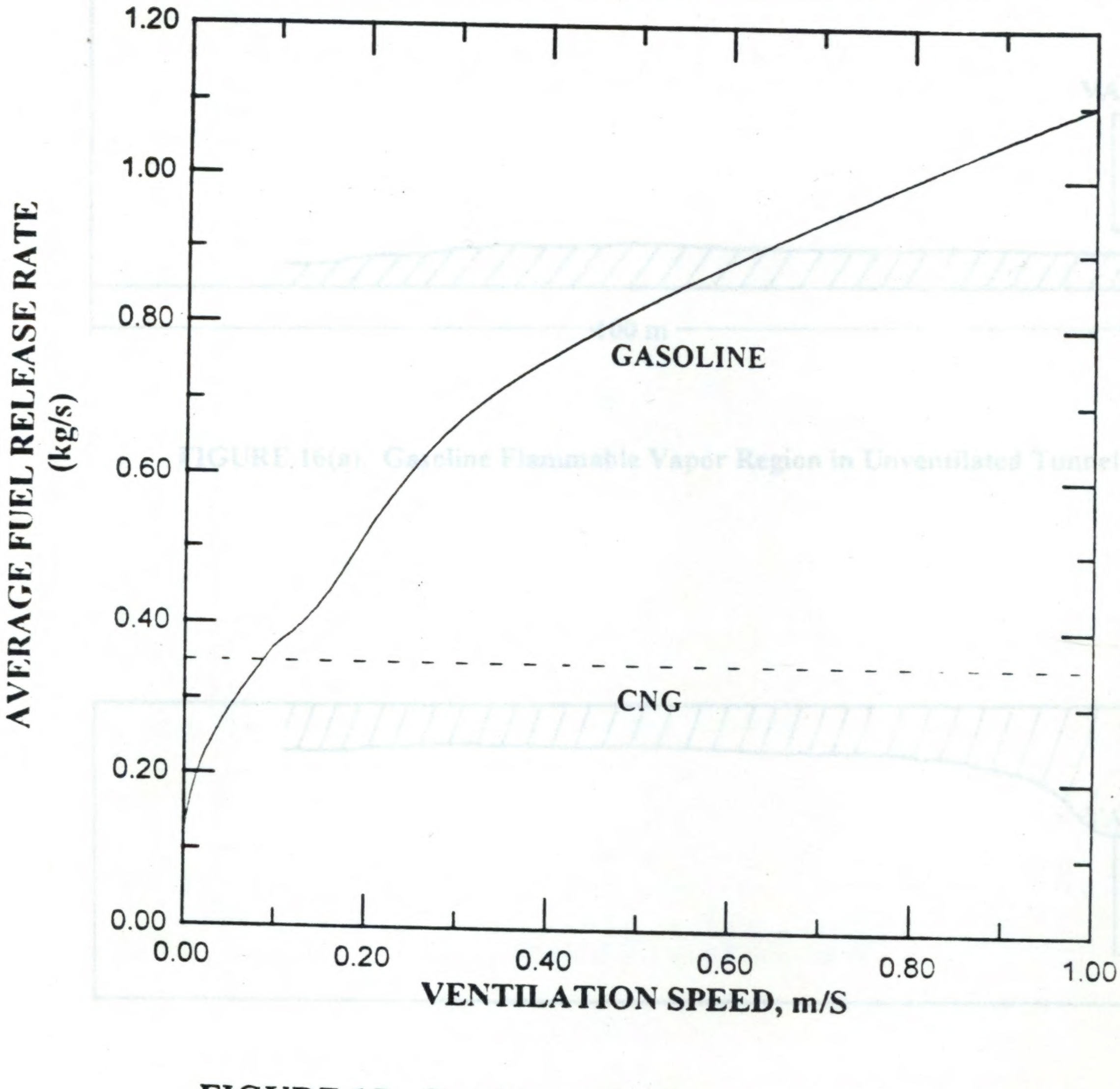

FIGURE 17. Gasoline and CNG Vapor Release Rates as a Function of Ventilation Velocity

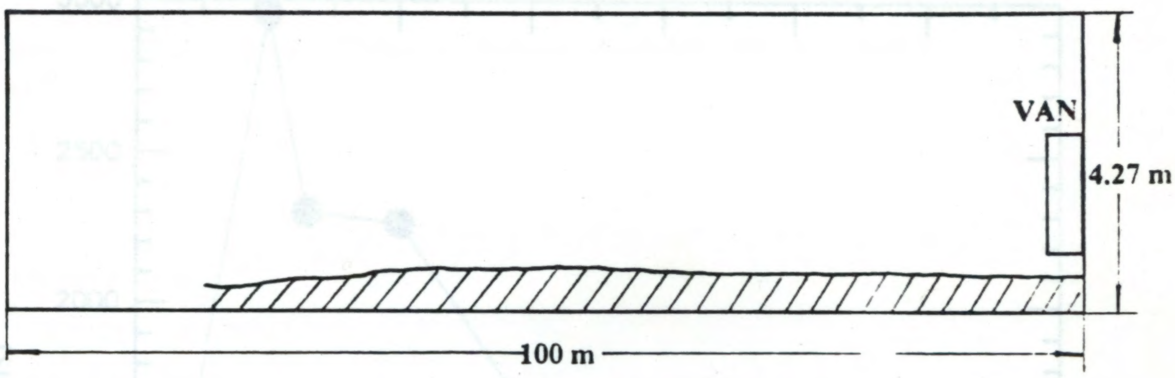

FIGURE 16(a). Gasoline Flammable Vapor Region in Unventilated Tunnel

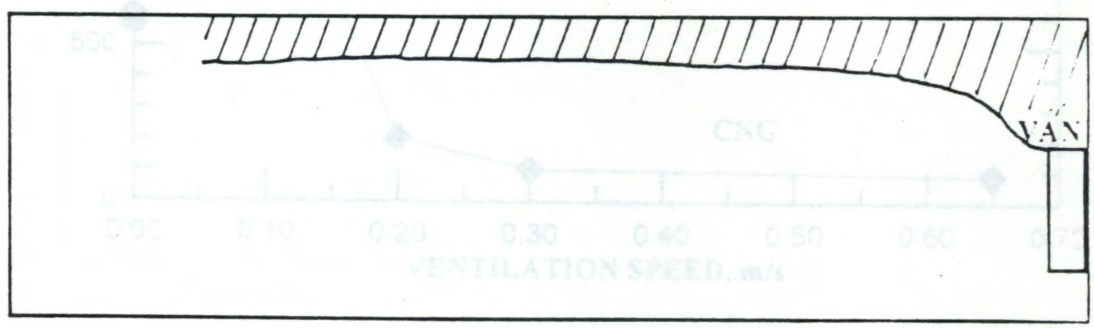

FIGURE 16(b). CNG Flammable Vapor Region at Unventilated Tunnel

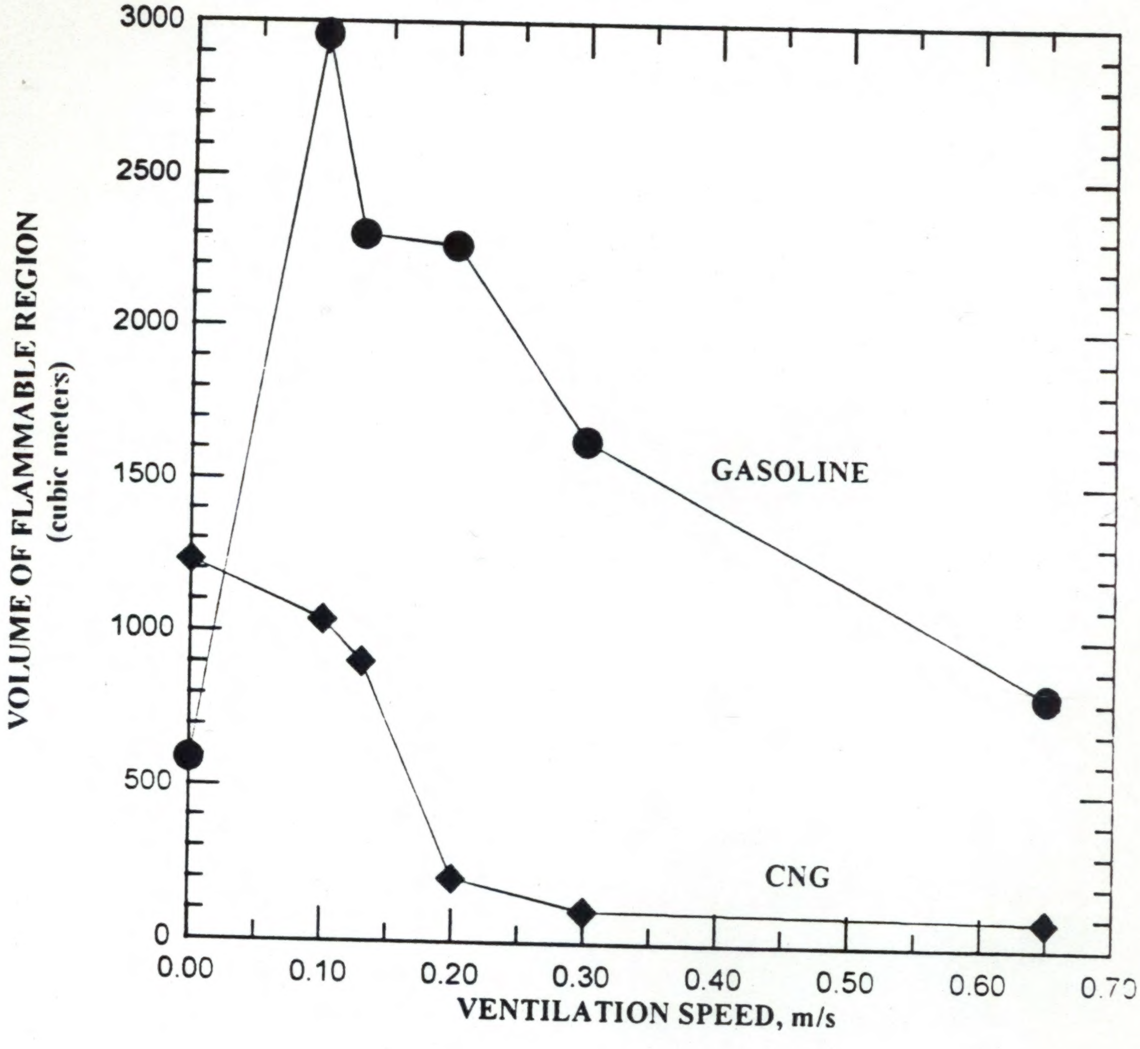

FIGURE 18. Estimated Volume of Flammable Region at Different Ventilation Speed